## Conduction-Band Structure of GaSb from Pressure Experiments to 50 kbar\*

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The pressure variation of the resistivity of S-, Se-, and Te-doped (n-type) GaSb has been studied to 50 kbar. All three types exhibit a saturation in resistivity at the highest pressures attained, although the resistivity of S- and Se-doped samples increases several orders of magnitude before saturation, in contrast to Te-doped samples, whose resistivity increases only by a factor of 14. The saturation in resistivity is due to the  $X_1$  minima becoming the lowest conduction-band edge at these pressures. Analysis of S- and Tedoped GaSb data, using a model of three different conduction-band minima (with the addition of one impurity level in the S-doped sample) and the known rate of motion of the bands, is consistent with an interband separation  $(E_{X_1} - E_{\Gamma_1})$  of  $0.315 \pm 0.015$  eV at zero pressure and a mobility ratio of  $\mu_X/\mu_{\Gamma}$  of  $\frac{1}{32}$ . The mobility ratio seems reasonable in comparison with *n*-GaAs.

### I. INTRODUCTION

T is well known that the lowest conduction-band minimum in GaSb lies at the center of the Brillouin zone<sup>1,2</sup> (k = 000) ( $\Gamma_1$  minimum), and a second set of minima lie along the (111) directions<sup>2-4</sup> in k space (L<sub>1</sub> minima) at about 0.08–0.09 eV above the  $\Gamma_1$ minimum. A third set of minima are expected at the (100) zone boundaries (X<sub>1</sub> minima) at a higher energy.<sup>5,6</sup> Ehrenreich<sup>6</sup> has estimated that these will lie about 0.3–0.4 eV above the  $\Gamma_1$  minimum, from several pieces of evidence.

With the application of hydrostatic pressure, the  $\Gamma_1$ minimum in GaSb shifts to higher energy relative to the valence-band maximum at a rate of about  $14.5 \times 10^{-3}$ eV/kbar,<sup>7</sup> and the  $L_1$  minima are expected to shift at about<sup>5</sup> 5×10<sup>-3</sup> eV/kbar or slightly faster.<sup>8</sup> Consequently, the  $L_1$  minima become the lowest set at a pressure of about 8 kbar.<sup>2</sup> Existing correlations among the pressure coefficients<sup>5</sup> of the conduction-band minima in 3-5 compounds Ge and Si indicate that the  $X_1$  minima in GaSb should shift slowly downward in energy with pressure, relative to the valence band, and should become the lowest set at still higher pressures. Indeed, optical energy-gap measurements on GaSb as a function of pressure by Edwards and Drickamer<sup>9</sup> have

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 <sup>2</sup> A. Sagar, Phys. Rev. 117, 93 (1960).
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<sup>6</sup> W. Paul, J. Appl. Phys. 32, 2082 (1961).
<sup>6</sup> H. Ehrenreich, J. Appl. Phys. 32, 2155 (1961).
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<sup>9</sup> A. L. Edwards and H. G. Drickamer, Phys. Rev. 122, 1149 (1961).

indicated that before 45 kbar there is a second crossover of the conduction-band minima.

Previous investigations have shown that the pressure variation of electrical resistivity of *n*-type samples can be analyzed to obtain information regarding the band structure of semiconductors at high pressures.<sup>10-12</sup> In the case of GaSb, Hall-coefficient and resistivity measurements to about 10 kbar by Sagar<sup>2</sup> have been analyzed to obtain the energy separation at zero pressure between the  $\Gamma_1$  minimum and the  $L_1$  minima. From resistivity measurements on *n*-type Te-doped GaSb to 30 kbar, Howard and Paul<sup>10</sup> concluded that the  $X_1$  minima may already be contributing appreciably to the conductivity near the high-pressure limit of their pressure range. More recently Kosicki, Paul, Strauss, and Iseler<sup>13</sup> have investigated the effect of hydrostatic pressure on the resistivity of Te-, Se-, and S-doped n-type GaSb to 28 kbar. They observed an exponential increase in the resistivity of S-doped samples over the entire pressure range and a similar rise with Se-doped samples in the 15-28-kbar range. This behavior was attributed to carrier freezeout to a deep S or Se level associated with the energetically higher-lying  $X_1$  minima, as the  $\Gamma_1$  and  $L_1$  minima moved to higher energy with pressure. In the case of Te-doped samples, however, there was only a small resistivity increase with pressure so that the donor levels associated with the  $\Gamma_1$  and  $L_1$  minima remain degenerate with these minima. No deeper level was indicated for pressures up to 28 kbar. The present study was undertaken to extend these room-temperature measurements to higher pressures, in the expectation that the crossover of the  $L_1$  and  $X_1$  minima might be

<sup>&</sup>lt;sup>10</sup> Review article by W. Paul and D. M. Warschauer, *Solids Under Pressure* (McGraw-Hill Book Co., New York, 1963).

<sup>&</sup>lt;sup>11</sup> J. Lees, M. P. Wasse, and G. King, Solid State Commun. 5, 521 (1967).

<sup>&</sup>lt;sup>12</sup> A. R. Hutson, A. Jayaraman, and A. S. Coriell, Phys. Rev. 155, 786 (1967).

<sup>&</sup>lt;sup>13</sup> B. B. Kosicki, W. Paul, A. J. Strauss, and G. W. Iseler, Phys. Rev. Letters 17, 1175 (1966).

Band parameter	Value used	Reference
$E_L - E_{\Gamma}$	0.085 eV	a
$(\partial/\partial P)(E_L - E_\Gamma)$	$-9 \times 10^{-3} \text{ eV/kbar}$	b
$(\partial/\partial P)(E_X - E_\Gamma)$	$-15.4 \times 10^{-3} \text{ eV/kbar}$	с
$\mu_L/\mu_{\Gamma}$	1/7.5	d
$\nu_{\Gamma}m_{\Gamma}^{*3/2}$	$(0.05)^{3/2}m_e^{3/2}$	е
$\nu_L m_L^{*3/2}$	$40mr^{*3/2}$	f
$\nu_X m_X^{*3/2}$	$1.4m_L^{*3/2}$	g

TABLE I. Values of band parameters used in calculation of resistivity increase.

Average of values are given in Refs. 2, 3, and 4.
References 5, 7, and 8; see text.
Reference 13.

<sup>d</sup> Reference 2 and fit to observed resistivity increase in Te-doped GaSb at 15 kbar. <sup>e</sup> Reference 1. <sup>f</sup> Ge value; Ref. 15. <sup>g</sup> Si value; Ref. 15.

observed in the resistivity-versus-pressure behavior. This in turn would yield direct information on interband energy separations and the mobility of electrons in the  $X_1$  minima. We report and discuss in this paper the results of resistivity measurements to about 50 kbar on S-doped, Se-doped, and Te-doped GaSb.

## **II. EXPERIMENTAL**

The pressure was generated in a piston-cylinder device using the Teflon cell technique.<sup>14</sup> For pressure medium, a 1:1 mixture of *n*-pentane and isoamyl alcohol was used. Piezoresistance measurements<sup>14</sup> using this mixture as the pressure medium have shown that hydrostatic pressure distribution prevails up to about 37 kbar at room temperature. At this pressure and temperature the mixture freezes and further application of pressure results in uniaxial stress which relaxes only over a long period of time. However, when the solidified pressure medium is heated, the uniaxial stress relaxes very rapidly, restoring the hydrostatic pressure distribution, which remains when the temperature is lowered again. Therefore at pressures higher than the freezing pressure of the medium at room temperature, the entire pressure plate was warmed to about 75°C by an externally wound heating tape and allowed to return to room temperature before resistivity measurements were taken. The samples were 4 mm by 4 mm square and usually about 0.25 to 0.3 mm thick. Indium or tin dots soldered (with an ultrasonic iron) to the four corners of the plate provided good ohmic contacts. Four coiled enamel-covered copper leads 0.006 in. in diam were soldered to the dots. In the case of S-doped samples thicknesses up to 2 mm were necessary because of the high resistivity of these specimens at high pressures. The plates were cut parallel to either the {111} or {100} crystallographic planes (except for Se-doped samples, which were not oriented) and the faces of the sample were oriented within the Teflon cell perpendicular to the piston-cylinder axis.



FIG. 1. Resistivity ratio versus pressure for S-, Se-, and Te-doped *n*-type GaSb at 300°K.

The resistivity measurements were made using two adjacent corners for the current contacts and the opposite two corners for the potential contacts. At each pressure a second resistivity value was obtained by permuting all contacts 90°, relative to their positions at the first measurement. Measurements were taken at room temperature at 2- or 4-kbar pressure increments and sufficient time was allowed between readings for the rise in temperature accompanying each pumping to disappear. For homogenous samples with good contacts, the resistivity ratios measured by the two combinations mentioned above were very close and the spurious voltage when no current was applied was very small; only data from such samples were considered trustworthy. In the case of Te-doped samples at pressures above 40 kbar the resistivity data were taken after relieving the uniaxial stress by heating the pressure medium. Because of the high resistivity of the S-doped samples at high pressures the above method presented some difficulty. Hence there is some degree of uncertainty in the saturation resistivity of the S-doped samples, which we will discuss below.

## III. DATA AND ANALYSIS

The effect of hydrostatic pressure on the resistivity of S-doped, Se-doped, and Te-doped GaSb is shown in Fig. 1. The present data are in good agreement with the results obtained by Kosicki et al.13 in the region of overlap of the two measurements. At the highest pressures

<sup>&</sup>lt;sup>14</sup> A. Jayaraman, A. R. Hutson, J. H. McFee, A. S. Coriell, and R. G. Maines, Rev. Sci. Instr. 38, 44 (1967).



FIG. 2. Experimental and calculated resistivity increase versus pressure for Te-doped GaSb: (1)  $E_X - E_{\Gamma} = 0.30 \text{ eV}, \mu_X/\mu_{\Gamma} = 0.032$ ; (2)  $E_X - E_{\Gamma} = 0.31 \text{ eV}, \mu_X/\mu_{\Gamma} = 0.0314$ ; (3)  $E_X - E_{\Gamma} = 0.32 \text{ eV}, \mu_X/\mu_{\Gamma} = 0.031$ . The circles are experimental points.

the resistivity curves for all three samples have saturated. We will show that the saturation in resistivity is a consequence of the  $L_1$  minima moving above the  $X_1$ minima in energy and we will determine the interband separation as well as the mobility ratio  $\mu_X/\mu_{\Gamma}$  from resistivity data.

We will analyze the data from S- and Te-doped samples, which represent the two extreme cases, using a model of three different conduction-band minima  $(\Gamma_1, L_1, \text{ and } X_1)$  with the addition of one impurity level for the S-doped sample, all of which move relative to each other in a known way (see Table I). The chargebalance equation for such a model is

$$N_D - N_A = n_D + n_\Gamma + n_L + n_X, \qquad (1)$$

where N<sub>D</sub> is the number of donors, N<sub>A</sub> the number of acceptors,  $n_{\Gamma}$ ,  $n_L$ , and  $n_X$  the carrier concentrations in the  $\Gamma_1$ ,  $L_1$ , and  $X_1$  minima, respectively, and  $n_D$  the electron concentration on donors, given by

$$n_D = N_D / \left( \frac{1}{g} \left( \frac{1}{g} \left( \frac{1}{g} \left( \frac{E_D - E_F}{g} \right) \right) \right).$$
 (2)

Here  $E_F$  is the Fermi energy, g the level degeneracy, and  $E_D$  the pressure-dependent energy of the donor level. The carrier concentrations are given by

$$n_{\alpha} = 2\nu_{\alpha} \left( \frac{2\pi m_{\alpha} kT}{h^2} \right)^{3/2} F_{1/2} \left( \frac{E_F - E_{\alpha}}{kT} \right), \quad \alpha = \Gamma, L, X \quad (3)$$

where  $\nu_{\alpha}m_{\alpha}^{*3/2}$  is the effective-mass density of states,  $E_{\alpha}$  is the pressure-dependent energy of the  $\alpha$  conduction band, and

$$F_{1/2}(\eta) = \frac{2}{\sqrt{\pi}} \int_0^\infty \frac{\epsilon^{1/2} d\epsilon}{1 + e^{(\epsilon - \eta)}} \tag{4}$$

is the Fermi-Dirac integral of order  $\frac{1}{2}$ . At a given pressure, Eq. (1) can be solved implicitly for  $E_F$  and the normalized resistivity can be written as

$$\rho/\rho_0 = \frac{\sigma_0}{\sigma} = \frac{n_{\Gamma}(0) + (\mu_L/\mu_{\Gamma})n_L(0) + (\mu_X/\mu_{\Gamma})n_X(0)}{n_{\Gamma}(P) + (\mu_L/\mu_{\Gamma})n_L(P) + (\mu_X/\mu_{\Gamma})n_X(P)},$$
 (5)

assuming that the mobilities are pressure-independent to first order.

In Table I we list the values of various room-temperature band parameters used in the calculation. The interband pressure coefficient  $\partial/\partial P(E_L-E_\Gamma)$  is a rounded-off value obtained from the measured<sup>7</sup> value of  $\partial/\partial P(E_{\Gamma}-E_{V})$  for GaSb (where  $E_{V}$  is the top of the valence band) and from the pressure coefficient  $\partial/\partial P(E_{L}-E_{V})$  measured<sup>5</sup> in Ge and corrected for the larger lattice constant of GaSb.<sup>8</sup> The effective masses used were the Ge effective mass for the  $L_1$  minima<sup>15</sup> and the Si effective mass for the  $X_1$  minima.<sup>15</sup> However, due to lack of inversion symmetry in GaSb, all the  $X_1$  minima must occur at the  $\langle 100 \rangle$  zone edge, which reduces the effective mass density of states of these minima to one half the value in Si.

We have treated as unknown the zero-pressure interband-energy separation  $(E_X - E_{\Gamma})$  and the assumed pressure-independent mobility ratio  $\mu_X/\mu_{\Gamma}$ , which are to be determined by fitting the pressure variation of the resistivity of S- and Te-doped GaSb.

#### Te-Doped GaSb

The salient features of the resistivity-versus-pressure curve shown in Fig. 1 for the Te-doped {111}-oriented GaSb sample are a rather rapid initial rise in the 1-10kbar region followed by only a very small increase up to about 30 kbar, a second large rise in the 30-40-kbar region, leveling off near 50 kbar. The resistivity of the Te-doped samples does not decrease when the temperature is raised at pressures near saturation. For this reason we believe that there is no carrier freezeout and the carrier concentration in the Te-doped samples remains constant at all pressures. Hence the term  $n_D$  in Eq. (1) can be ignored. The two resistivity increases that are seen must therefore be mainly due to mobility decreases as carriers are transferred from the  $\Gamma_1$  to the  $L_1$  minima and finally from the  $L_1$  to the  $X_1$  minima. Using this model we obtain a mobility ratio of  $\mu_L/\mu_{\Gamma}$ =1/7.5 from the first resistivity increase saturating at 15 kbar, which is consistent with the value quoted by Sagar.<sup>2</sup>

In Fig. 2 three resistivity-versus-pressure curves calculated using different values of  $E_X - E_{\Gamma}$  and  $\mu_X/\mu_{\Gamma}$  in Eq. (5) are compared with the experimental data for this sample. In each case the mobility ratio  $\mu_X/\mu_{\Gamma}$  was determined from the saturated value of resistivity of 50 kbar, and the range of values of  $E_X - E_{\Gamma}$  was dictated by the start of the resistivity rise at about 30 kbar. It seems evident from this figure that the best value for  $E_X - E_{\Gamma}$  lies between 0.30 and 0.32 eV.

Resistivity-versus-pressure runs were also made on  $\{111\}$ - and  $\{100\}$ -oriented plates of Te-doped material, without relaxing the uniaxial stress that results above the freezing pressure of the fluid mixture. While the

 $<sup>^{15}</sup>$  G. Dresselhaus, A. F. Kip, and C. Kittel, Phys. Rev. 100, 618 (1955).

resistivity data for the two orientations are in excellent agreement in the hydrostatic pressure regime, the presence of uniaxial stress causes them to deviate at the high-pressure end. Above the freezing pressure (>38)kbar) the resistivity of the {100}-oriented sample decreases very rapidly, compared to the {111}-oriented sample. This decrease in resistivity is due to the effect of uniaxial stress (acting along [100] direction of the {100}-oriented plate) which splits the degeneracy of the three  $X_1$  minima in such a way as to lower the resistivity measured in the plane perpendicular to the direction of compressive stress. With the {111}-oriented plate the uniaxial stress which is applied along the [111] direction acts symmetrically on these three minima and hence does not split their degeneracy. This piezoresistivity effect is consistent with the assumed (100) symmetry of the minima which are lowest at the highest pressures.

#### S-Doped GaSb

It has been shown that the exponential increase in resistivity with pressure above 10 kbar in S-doped and above 15 kbar in Se-doped GaSb is due to carrier freezeout to a S- or Se-donor level, which moves away from the  $L_1$  conduction band, the lowest in this pressure range.<sup>13</sup> From this rate of motion it has been deduced that the impurity level moves at almost exactly the same rate under pressure as is expected of the  $X_1$ conduction band.<sup>5</sup> This model is therefore consistent with the observation of an eventual saturation in resistivity of both S- and Se-doped materials, when the  $X_1$  band has become the lowest and the  $L_1$  band is depleted of all carriers. From these considerations we assign to both pressure coefficients  $\partial/\partial P(E_X - E_\Gamma)$  and  $\partial/\partial P(E_D - E_\Gamma)$  a value of  $-15.4 \times 10^{-3}$  eV/kbar (see Table I). Furthermore it was previously shown<sup>13</sup> that the S level responsible for carrier freezeout is actually 0.075 eV below the lowest conduction-band edge at zero pressure. Since both the zero-pressure donorionization energy and the rate at which the  $L_1$  band moves away from the S impurity level are known, the resistivity increase of S-doped GaSb can be calculated without introducing any other unknown parameters than the two which existed in the Te-doped GaSb calculation.

Qualitatively it is evident that either an increase in  $\mu_X/\mu_{\Gamma}$  or a decrease in  $E_X - E_{\Gamma}$  will cause the start of the saturation in the calculated resistivity curve to occur at lower pressure. Therefore it is not surprising that there exists a whole set of pairs of values for  $E_X - E_{\Gamma}$  and  $\mu_X/\mu_{\Gamma}$ , each pair giving essentially the same calculated resistivity curve. In Fig. 3 we show a resistivity curve (curve 1) calculated to have the same saturation resistivity as is observed in the data for S-doped GaSb. In Fig. 4 is shown a graph of  $E_X - E_{\Gamma}$  versus  $\mu_X/\mu_{\Gamma}$ . All of the pairs of values represented by curve 1 of Fig. 4 will give the calculated curve 1 shown in Fig. 3 which reaches a value of 42 000 in resistivity increase at 50 kbar. In Fig. 4 we have also plotted on



FIG. 3. Experimental and calculated resistivity increase versus pressure for S-doped GaSb: (1) resistivity saturates at 42 000  $\rho_0$ ; (2) resistivity saturates at 70 000  $\rho_0$ . The circles are experimental points.

curve 2 the values for those parameters used in computing the three curves shown in Fig. 2 for Te-doped GaSb. Assuming that  $\mu_X/\mu_{\rm F}$  has the same value for both



FIG. 4. Mobility ratio versus interband energy separation for calculated resistivity curves: (1) S-doped—resistivity saturates at 42 000  $\rho_0$ ; (2) Te-doped; (3) S-doped—resistivity saturates at 70 000  $\rho_0$ .



FIG. 5. Band structure of GaSb at zero pressure. Arrows indicate magnitude and direction of movement of conduction-band extrema under increasing pressure, relative to the top of the valence band.

Te- and S-doped GaSb (ionized impurity scattering usually dominates only at much lower temperatures) the point of intersection of curves 1 and 2 determines the most consistent values for our unknown parameters; these values are  $E_X - E_{\Gamma} = 0.307$  eV and  $\mu_X/\mu_{\Gamma} = 1/31$ . Looking back at Fig. 2, it is seen that this set of values gives good agreement with the data on Te-doped GaSb.

## IV. DISCUSSION

The probable error in our values of  $E_X - E_{\Gamma}$  and  $\mu_X/\mu_{\Gamma}$  derives from the uncertainty of the saturationresistance values, particularly those for the S-doped sample. In the case of Te-doped GaSb we were able to make resistivity measurements after relieving the nonhydrostatic stress, and hence there is negligible error in the experimentally determined saturated-resistance ratio. The presence of nonhydrostatic stress at high pressures introduces some uncertainty in the saturation resistivity ratio of the S-doped sample, although the sample geometry and orientation was chosen to minimize the effect of this stress. Measurements on Te-doped GaSb of similar orientation and geometry under similar nonhydrostatic conditions, lead us to believe that the observed saturation resistivity ratio in the case of Sdoped samples may actually be somewhat smaller than would be the case if hydrostatic pressure distribution alone were present.<sup>16</sup> Therefore, the value of  $42\ 000$  for the saturation-resistivity ratio for the S-doped GaSb represents a lower limit. From the observed increase in

saturation resistivity of Te-doped samples after the stress was relieved, we estimate that the saturation resistivity in S-doped GaSb could be as large as 70 000. We have therefore computed resistivity curves for S-doped GaSb on this basis and show this also in Fig. 3 (curve 2). Values for  $\mu_X/\mu_{\Gamma}$  versus  $E_X - E_{\Gamma}$  which will yield this curve are shown in Fig. 4 (curve 3). The intersection of curve 3 with curve 2 for Te-doped GaSb gives a value for  $E_X - E_{\Gamma} = 0.319$  eV, which may be regarded as the upper limit for this parameter, from our measurements.

From Fig. 4 we may state that the most probable value of  $E_X - E_{\Gamma}$  is 0.313 $\pm$ 0.006 eV. In Fig. 3, however, the curve which saturates at 70 000 gives best agreement with the experimental data at pressures below 38 kbar (the freezing point of the pressure medium). In view of the nonhydrostatic stress above this pressure it is possible to consider curve 2 a better fit to the experimental data than curve 1. This view would favor the higher limit (0.319 eV) of our stated range for  $E_X - E_{\Gamma}$ , and in fact we observe in Fig. 2 that the resistivity calculated assuming essentially this same interbandseparation value (0.32 eV, curve 3) fits the experimental data for Te-doped GaSb much better than an interband separation between 0.30 and 0.31 eV. However, even though this higher value seems indicated, we will continue to regard the average value of 0.313 eV as the best which can be determined from our data, in the absence of an observed hydrostatic resistivity saturation of 70 000 for S-doped GaSb. Finally, allowing for a 5%possible error in the value of the pressure coefficients used in the calculation, and rounding of our value to the nearest 5 meV, we obtain a value of  $0.315 \pm 0.015$  eV.

In Fig. 5 the relative energies of the principal conduction- and valence-band extrema of GaSb are drawn using the value for the interband separation  $E_X - E_{\Gamma}$ determined above. We have also schematically indicated the pressure coefficients of the three conduction bands, relative to the valence band, by vectors whose length is proportional to the magnitude of the pressure coefficient. The value of  $0.315 \pm 0.015$  eV which we obtain for the interband separation  $E_X - E_{\Gamma}$  is consistent with previous estimates<sup>6</sup> of this parameter. Edwards and Drickamer<sup>9</sup> observed a change in the sign of the pressure coefficient of the energy gap of GaSb above 45 kbar which indicates that the  $L_1$  and  $X_1$  bands have crossed at lower pressure. This observation is consistent with the band crossover pressure of about 35 kbar which we have obtained from our calculation and fitting to the experimental results.

Becker, Ramdas, and Fan<sup>3</sup> have reported an infrared absorption threshold at about  $3.3 \,\mu$  in *n*-type GaSb. Subsequently Haga and Kimura<sup>17</sup> analyzed the data of Becker *et al.* under the assumption that the absorption was caused by indirect transitions from the populated  $\Gamma_1$  conduction band to the higher lying  $X_1$  band. The

<sup>&</sup>lt;sup>16</sup> In Fig. 1 this effect of nonhydrostatic stress is clearly evident as a discontinuity in the resistivity slope of the nonoriented Se-doped GaSb sample at 40.5 kbar, which is just above the freezing point of the pressure fluid.

<sup>&</sup>lt;sup>17</sup> E. Haga and H. Kimura, J. Phys. Soc. Japan 19, 1596 (1964).

value of 0.3 eV which they obtained from this analysis is in good agreement with our finding.

We have assumed that the mobility ratios  $\mu_L/\mu_{\Gamma}$  and  $\mu_X/\mu_{\Gamma}$ , which appear in Eq. (5), can be regarded as pressure independent in our analysis. However, it is to be noted that above 10 kbar the  $\Gamma_1$  band is essentially depleted of electrons; therefore, above this pressure, the assumed pressure independence of  $\mu_L/\mu_{\Gamma}$  and  $\mu_X/\mu_{\Gamma}$ simply implies constancy of the mobilities  $\mu_L$  and  $\mu_X$ with pressure. This assumption for  $\mu_L/\mu_{\Gamma}$  (or  $\mu_L$ ) is supported by our experiments from the data on Tedoped GaSb; the resistivity is seen to rise only very slowly between 10 and 25 kbar. From the calculated curves of Fig. 2 we see that this rise can be accounted for almost entirely by the transfer of carriers into the low-mobility  $X_1$  band, which begins in this pressure range. We believe the assumption of pressure independence of  $\mu_X/\mu_{\Gamma}$  above the crossover pressure is equally valid, as indicated by the saturation to an

almost constant value of resistivity in Te-doped GaSb at the highest pressures. Also, our value for  $\mu_X/\mu_{\Gamma}$ appears a reasonable one in comparison with what has been reported for  $\mu_X/\mu_{\Gamma}$  for GaAs.<sup>11,12</sup> Finally, the absence of a maximum in the resistivity at or near the pressure at which the bands cross implies that pressuredependent interband scattering, which would tend to decrease the mobility in this range, is not dominant in this material.18

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<sup>18</sup> Marshall I. Nathan, William Paul, and Harvey Brooks, Phys. Rev. 124, 391 (1961).

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# Higher Absorption Edges in 6H SiC

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The absorption of 6H SiC was measured for photon energies up to 4.9 eV, where the absorption coefficient is  $4.6 \times 10^4$  cm<sup>-1</sup>. Samples as thin as  $1.8 \mu$  were prepared by grinding and polishing. Indirect absorption edges were found at 3.0, 3.7, and 4.1 eV. A fourth absorption edge at 4.6 eV could not be positively identified as direct or indirect.

### I. INTRODUCTION

**D**REVIOUS absorption measurements<sup>1</sup> in 6H SiC revealed exciton and phonon structure in the indirect interband edge near 3 eV. One earlier report<sup>2</sup> showed measurements to 4.4 eV, but indicated no additional absorption thresholds at the higher energies. Recent reflectance measurements showed some weak structure at 4.6 eV which may be evidence of a direct transition.<sup>3</sup> The object of the present investigation was to look for additional structure in the absorption edge, and especially to try to locate the first direct edge. This is a matter of considerable importance for the calculation of the 6H SiC band structure, using an empirical method,<sup>4</sup> in which the value of the smallest direct gap is an important parameter to be fitted.

We were able to prepare samples of 6H SiC as thin as  $1.8 \mu$ , by grinding and polishing, and we made

absorption measurements to nearly 4.9 eV. The typical crystal habit of hexagonal SiC restricted our measurements to one polarization direction  $(E \perp c)$ , but this is the direction for which the reflectance measurements were made. The results show three successive indirect edges at approximately 3.0, 3.7, and 4.1 eV, and a fourth absorption edge at 4.6 eV, which also appears to be indirect. However, as explained below, it becomes increasingly difficult to distinguish between direct and indirect edges as one goes to higher energies. An indirect edge at 4.6 eV is incapable of explaining the reported structure in the reflectivity. We conclude that the character of the 4.6-eV edge has not yet been established.

## **II. ABSORPTION EDGES**

The analysis of absorption edges in 6H SiC presents some new problems because of the unusual polytype structure,<sup>5</sup> and because of the wide energy range over which the transitions are thought to be indirect. At the

<sup>&</sup>lt;sup>1</sup>W. J. Choyke and Lyle Patrick, Phys. Rev. **127**, 1868 (1962), Sec. VII. <sup>2</sup>H. R. Phillip, Phys. Rev. **111**, 440 (1958). <sup>8</sup>B. E. Wheeler, Solid State Commun. **4**, 173 (1966). <sup>4</sup>M. L. Cohen and T. K. Bergstresser, Phys. Rev. **141**, 789

<sup>(1966).</sup> 

<sup>&</sup>lt;sup>6</sup> A. R. Verma and P. Krishna, *Polymorphism and Polytypism* in Crystals (John Wiley & Sons, Inc., New York, 1966).